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Economic analysis of fuel cell installations at commercial buildings including regional pricing and complementary technologies

Dustin McLarty[a,*], Jack Brouwer[b], Chris Ainscough[c]

[a] Clean Energy Systems Integration Laboratory, Washington State University, Pullman, WA 99164, USA
[b] National Fuel Cell Research Center, University of California, Irvine, CA 92697, USA
[b] National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA

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ABSTRACT

This paper presents results from sensitivity studies conducted using the Distributed Generation Build-out Economic Assessment Tool (DG-BEAT). The viability of meeting commercial building loads with a stationary fuel cells is studied under different conditions of electricity pricing, dispatch strategies, and complementary technologies. Key findings support the notion that fuel cells are becoming economically viable alternatives in California, New York and Connecticut at installed costs of $7000–10,000/kW. Michigan is identified as another state well suited to fuel cell development with heat recovery. Fuel cell installations reduce net carbon emissions for commercial buildings by 20–30% when compared to local, time-resolved, grid emissions. Grid sell-back, at 50% retail price, significantly improves the economics of a base load fuel cell, but has little impact for a dispatchable system. At installed costs below $5000/kW, load following capability results in significant additional cost reductions as the generating capacity is increased beyond the building's base load requirements. Complementary technologies such as chillers and thermal storage have a pronounced impact, particularly in warmer climates. Installing fuel cells paired with electric chillers and thermal storage in Florida at buildings with exceptionally high air conditioning demands can achieve the same economic benefit as a typical New York building.

1. Introduction

This paper presents analyses conducted using the Distributed Generation Build-Out Economic Assessment Tool (DG-BEAT) [1]. The aim of this paper is to perform sensitivity analyses of the primary factors influencing the economic viability of stationary fuel cell systems for commercial buildings in the United States. Some of the important factors identified by others and that are also considered here include: commercial electricity and gas rates [2], time-of-use and demand charges, building dynamics, climate impacts, fuel cell control capability [3–5], and balance of system components such as thermal or electric energy storage [6,7] and absorption chiller heat recovery [8,9].

Briefly, the DG-BEAT tool performs a detailed energy dispatch to meet an entire year of high resolution (15-min) building energy data developed in Energy Plus [10,11]. The dispatch considers key constraints such as generator ramp rates and turndown ratios, grid interconnection limits, and energy storage charging/discharging inefficiencies. Non-linear efficiency curves are interpolated to determine annual energy use, emissions, and costs corresponding to the dispatch. The same analysis features can be applied to a variety of distributed generation technologies used to meet a portion or all of the energy demands at a single building or multiple buildings (e.g., campus). Balance of system components (e.g., absorption chilling, energy storage) change the dynamics of building-generator system by coupling or de-coupling the generation with cooling demands or electric demands.

Generator dynamics and dispatch are supported by physical modeling experience [12–14], and coupled with datasets for renewable energy generation (e.g. insolation and wind speed profiles) [15,16], utility rate structures [17], spatially and temporally resolved grid emissions of CO_2, NO_x, and SO_x [18]. The distribution of commercial buildings in all 50 states is divided into 16 categories. A detailed description of the open access software, DG-BEAT, can be found in [1].

Stationary fuel cells have been successfully deployed at a number of commercial buildings including supermarkets [19], office buildings [20], and hotels [21]. Many of America's largest companies are deploying stationary fuel cells in applications ranging from data centers to onion processing [22]. Additional commercial

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[*] Corresponding author.
E-mail address: dustin.mclarty@wsu.edu (D. McLarty).

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Nomenclature

CHP	combined heat and power
DG	distributed generation
DG-BEAT	Distributed Generation Build-out Economic Assessment Tool
FC	fuel cell
kW	kilowatt
MW	megawatt
NPC	net present cost
SOFC	solid oxide fuel cell
TES	thermal energy storage
TOU	time of use
Variables	
t_{on}	begin of on-peak electricity rates
t_{off}	end of on-peak electricity rates
r_{on}	duration of ramp from off-peak output to on-peak output
r_{off}	duration of ramp from on-peak output to off-peak output
$demand_t$	demand at time interval t
DG_t	output at time interval t

applications for which fuel cells have demonstrated economic viability such as biogas applications at wastewater treatment [23] and landfill facilities, backup power [24], and tri-generation with co-production of hydrogen [25] are not currently considered. Residential fuel cell applications require an order of magnitude cost reduction to become cost effective [26,27] and are not considered at this time.

Analyses of stationary fuel cell systems have often considered only the electric output, while some have included an SOFC with hydrogen co-production [4], electric energy storage [7], thermal storage [28] or absorption chilling [8]. Some limited sensitivity studies suggested a strong dependence upon the relative costs of electricity and natural gas, the presence of net-metering tariffs, and additional CHP systems e.g. electric and thermal storage [4]. Absorption chillers were shown to be well suited for thermodynamic integration with high temperature fuel cells although the economic benefit is undetermined [9]. The literature suggests potential for improved economic performance from applying a dispatchable fuel cell to a building demand using either a simple [29] or complex physical model of the system [3].

Most prior assessments of DG technology agree that only specific combinations of local energy costs, building type, DG system and dispatch strategy result in energy, cost, and emissions savings to buildings. Simulations are typically conducted on a case-by-case basis. In an effort to accelerate the simulation process, an analysis by Pruitt et al. developed a series of mathematical formulas for the determination of savings and losses using just a few characteristics of the building profile and rate structure [2]. The current work supports the findings of these previous studies and further expands upon the comparative study capabilities of the literature with a substantially more rigorous methodology and consideration of a much broader set of buildings, generators, and energy rates.

The largest factor impacting the economic viability of fuel cells is the value of energy conversion, calculated as the difference between the local fuel (i.e. natural gas) and electricity prices. Fig. 1 presents this value for the commercial sector, utilizing the same energy cost projections as DG-BEAT. The local favorability to distributed generation technologies is illustrated with respect to a baseline "spark spread" determined from the national average for electric and gas energy costs, and is highly sensitive to changes in the future energy cost projections. Higher electric rates and lower gas rates are favorable to fuel cells. Most geographic analysis of fuel cell viability will reflect this value of energy conversion, see for example Fig. 3. Thus, to identify impacts of different operating modes and complementary technologies, most results are presented as comparisons to the initial baseline case of Fig. 3.

Table 1
List of test scenario conditions.

Scenario	Components	Control	Electric rate	Grid sellback
1	FC + CHP	Base load	Non-TOU	No
2	FC + CHP	Base load	TOU	No
3	FC + CHP	Diurnal	TOU	No
4	FC + CHP	Base load	Non-TOU	Yes
5	FC + CHP	Load follow	TOU	No
6	FC + CHP + Chill + TES	Load follow	TOU	No
7	FC + CHP + AbChill	Base load	Non-TOU	No

These seven scenarios, mapping features, and national commercial building datasets are included features of the DG-BEAT tool, and can be readily repeated with generator specific costs and performance as well as specific financing terms and updated utility pricing or forecasts. Further inquiries into specific features of each state, or the impact of various state incentives [17], are relevant to fuel cell deployment but omitted here due to their temporary nature. This work brings focus to broader regional trends and DG system design considerations.

2. Methodology

This study presents seven test cases evaluated using the national analysis feature of DG-BEAT. Numerous scenarios were evaluated, but the scenarios presented in Table 1 were selected to illustrate particularly relevant impacts on the stationary fuel cell market. All scenarios outlined in Table 1 included a generic SOFC module with 60% fuel-to-electric conversion efficiency. Heat recovery, to an exhaust temperature of 100 °C, is applied to the heating demand coincident with the electric generation. Scenarios 6 and 7 consider the addition of electric chillers with thermal storage or the addition of an absorption chiller. Scenarios 1, 4 and 7 consider a fixed price of purchased electricity, while scenarios 2, 3, 5, and 6 consider time-of-use (TOU) pricing. All seven scenarios include a simulation of 16 building varieties across the lower 48 states. The unique energy costs and climates in Alaska and Hawaii merit separate analysis.

Each simulation consisted of loading the appropriate building energy profile, specific to each states climate, determining the fuel cell and balance of system capacities (i.e. chillers, thermal storage, batteries) according to the control strategy and export allowances, dispatching the energy systems according to the control strategy and export allowances, calculating the baseline and dispatched costs and emissions, and performing a net-present-cost analysis of the buildings energy expenses over the lifetime of the DG system.

There are a variety of methods available to determine the size of the fuel cell and balance of system technology built into DG-BEAT. Fig. 2 illustrates the trade-offs between several sizing methods. The presented trends are not precise but are indicative of the decision making considerations when sizing and operating a combined cooling, heating and power (CCHP) system. Meeting a greater proportion of the demand requires increasingly expensive technology to meet peak capacity and respond to building dynamics. The increase in size and decrease in operating hours of the self-generation technology causes an exponential rise in the relative equipment costs. As the self-generation is better utilized (operates a greater proportion of the time), energy and operations costs increase, while utility charges are reduced.

The sum of these three curves results in a convex curve which can be optimized for one of three objectives: (a) the